DTIC FILE COPY

AD-A217 584

(2)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
Jan 1984

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
PLASMA DYNAMICS

5. FUNDING NUMBERS

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Cambridge, Massachusetts 02139

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR 84-0026

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
BLDG 410
BAFB DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR-TR- 90-0034

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

14. SUBJECT TERMS

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (890104 Draft)
Prescribed by ANSI Std. Z39-18
298-01

Massachusetts Institute of Technology

Research Laboratory of Electronics

Cambridge, Massachusetts 02139

Reprinted from

RLE Progress Report No. 126, January 1984

18. Plasma Dynamics

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18.1 Relativistic Electron Beams and Generation of Coherent Electromagnetic Radiation

National Science Foundation (Grants ECS82-00646 and ECS82-13485)
U.S. Air Force - Office of Scientific Research (Contracts F33615-81-K-1426, F49620-83-C-0008, and AFOSR-84-0026)
U.S. Navy - Office of Naval Research (Contract N00014-83-K-2024)
Sandia National Laboratory (Contracts 31-5606 and 48-5725)
George Bekefi, Ruth E. Shefer

Relativistic electron beam research at M.I.T. focuses on the generation of intense coherent electromagnetic radiation in the centimeter, millimeter and submillimeter wavelength ranges. The primary radiation mechanism which is being studied at the present time is the free electron laser instability which is excited when an electron beam passes through a spatially periodic, transverse magnetic field (wiggler field). This instability is characterized by axial electron bunching and has emission wavelengths associated with the Doppler upshifted wiggler periodicity.

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Intense coherent sources of centimeter and millimeter wavelength radiation find applications in many diverse fields of research and technology including heating and diagnostics of thermonuclear fusion plasmas, photochemistry, solid state physics, and biophysics. One advantage of free electron systems such as the free electron laser are the very high predicted efficiencies which may be attained. Another important advantage is frequency tunability which results from the fact that the radiation frequency is not locked to an atomic or molecular transition or to an electromagnetic mode of a resonant structure but is instead determined by the velocity of the beam electrons.

The experimental facilities available to this group include three pulsed high voltage accelerators capable of delivering up to 100 kA of current at 0.5 to 1.5 MV. Their characteristics are summarized below:

Pulserad 110 A	
Voltage	1.5 MV
Current	20 kA
Pulse Length	30 ns

Pulserad 615 MR	
Voltage	0.5 MV
Current	4 kA
Pulse Length	1 μs

Nereus	
Voltage	0.6 MV
Current	100 kA
Pulse Length	30 ns

In the following sections, various radiation generation experiments presently being carried using the above electron beam generators are discussed.

a. The Rippled Field Magnetron (Cross-Field Free Electron Laser)

To achieve efficient conversion of energy from a stream of free electrons to electromagnetic radiation, near synchronism must be attained between the velocity of the electrons and the phase velocity of the wave. In cross-field devices, of which the magnetron is a typical example, this synchronism occurs between electrons undergoing a $v = \vec{E}_0 \times \vec{B}_0$ drift in orthogonal electric and magnetic fields, and an electromagnetic wave whose velocity is reduced by a slow-wave structure comprised of a periodic assembly of resonant cavities. The complex system of closely spaced resonators embedded in the anode block limits the conventional magnetron to wavelengths in the centimeter range. Moreover, at high voltages typical of relativistic magnetrons, RF or dc breakdown in the electron beam interaction space, and at the sharp resonator edges poses serious problems.

The rippled-field magnetron is a novel source of coherent radiation devoid of physical slow-wave structures and capable of radiating at much higher frequencies than a conventional magnetron. The

configuration of the anode and cathode is similar to the so-called "smooth-bore" magnetron, but it differs from the latter in that the electrons are subjected to an additional field, an azimuthally periodic (wiggler) magnetic field B_ω oriented transversely to the flow velocity v. The resulting $-e\vec{v} \times \vec{B}_\omega$ force gives the electrons an undulatory motion which effectively increases their velocity, and allows them to become synchronous with one of the fast TE or TM electromagnetic modes (phase velocity > c) characteristic of the smooth-bore magnetron.

The magnetron configuration is cylindrical rather than linear as in conventional FEL's, and the system is therefore very compact. The cylindrical geometry also allows for a continuous circulation of the growing electromagnetic wave, and because of this internal feedback, the rippled-field magnetron is basically an oscillator rather than an amplifier as is the case of the FEL.

We have obtained measurements of millimeter-wave emission from the rippled field magnetron.[1] In these experiments the magnetic wiggler field is produced by a periodic assembly of samarium-cobalt bar magnets positioned behind the smooth, stainless steel electrodes. Maximum radiated power in the 26.5-60 GHz frequency band is obtained with a wiggler periodicity of 2.53 cm and a wiggler field amplitude of 1.96 kG. Under these conditions a narrow band spectral line is observed with a line width at the half power points of less than 2.2 GHz. The center frequency of this line can be varied from 32 GHz to 46 GHz by varying B_z between 5.8 kG and 9 kG. No deterioration in line profile is observed over this range. The total radiated power above 26.5 GHz measured with this wiggler is 300 kW; which is more than a factor of thirty above the broadband noise observed with no wiggler.

We note that this device differs from the conventional FEL in that the electron source (the cathode) and the acceleration region (the anode-cathode gap) are integral parts of the RF interaction space. This makes for high space-charge densities which result in large growth rates of the instability; but it has the disadvantages that the current density and position of the interacting electrons in the gap are difficult to control. In the section below we describe an experiment in which a thin, hollow rotating electron beam is injected into the cylindrical wiggler structure. This configuration eliminates the need for the accelerating anode-cathode electric field E_0 and allows us to easily control both the current density and the beam dynamics in the interaction gap.

b. A Rotating Beam Free Electron Laser

In this section we describe a variation on the rippled field magnetron in which a rotating electron beam interacts with a rippled magnetic field.[2] This work is being carried out at the University of Maryland in collaboration with Prof. W.W. Destler.

In the experiments, a 12 cm diameter, hollow, rotating electron beam (2 MeV, 1-2 kA, 5 ns) is generated by passing a hollow non-rotating beam through a narrow magnetic cusp. The rotating beam performs helical orbits ($\beta_{\theta} \simeq .95$, $\beta_z \simeq .2$) downstream of the cusp in an axial guide field of about 1450 Gauss. Radiation is produced by the interaction of the beam with an azimuthally periodic wiggler magnetic field produced by samarium cobalt magnets located interior and exterior to the

beam. In the present work, the wiggler field has an amplitude of about 1300 Gauss, six spatial periods around the azimuth, and a periodicity of 6.28 cm.

We have observed at least 200 kW of radiation above 91 GHz in initial experiments, a result consistent with the frequency expected for a linear free electron laser operating with comparable parameters. Radiation at these frequencies is not observed in the absence of the wiggler field. Numerical calculations of the electron orbits in the combined axial and wiggler fields indicate that the orbits are relatively unperturbed in the r–θ plane and that the perturbation of the orbits due to the wiggler is primarily axial, as desired. Measurements of the actual circulating current exciting the wiggler region with and without the wiggler magnets in place confirm that the wiggler field does not have a seriously adverse effect on the electron orbits.

Measurements of the radiation spectrum using a grating spectrometer and studies of the effects of wiggler amplitude and periodicity are currently underway.

c. A Low Voltage Free Electron Laser

Many theoretical studies have been devoted to free electron lasers comprised of an electron stream traversing a periodic, circularly polarized magnetic (wiggler) field, as can be generated with bifilar, helical, current-carrying wires. The electron dynamics in these systems exhibit simple properties that have considerable theoretical appeal. However, from the experimental point of view large amplitude, circularly polarized wiggler fields are difficult to attain because of the large currents that are required in their windings; and for long pulse or steady-state operation, bifilar conductors may be entirely out of the question. In view of the above, studies of free electron lasers have begun in which the electron beam is subjected to a periodic, linearly polarized transverse magnetic field such as can be produced, for example, by an assembly of permanent magnets.

An experiment is underway to investigate the microwave and electron beam characteristics of a Free Electron Laser amplifier using a linear wiggler field. In this experiment, a 35 keV, 1A electron beam is produced by a thermionic cathode. The beam pulse width is 1-5 μsec, with a 0.001 duty cycle. A guiding axial magnetic field, generated by a series of D.C. powered, water cooled solenoid coils, is variable up to a maximum of $B_o = 3$ kG. This field both prevents radial expansion of the beam and allows investigation of the FEL gain near the cyclotron resonance condition, $k_o V_{\parallel} - \Omega_o/\gamma = 0$. ($K_o = 2\pi/\ell$, ℓ = wiggler period, $\Omega_o = (eB_o/m_o)$, $\gamma = (1 - \beta^2)^{-1/2}$). When this resonance condition is satisfied, the cyclotron wavelength of an electron in the uniform guiding magnetic field equals the wiggler periodicity. Enhanced growth of the radiation field is predicted as this condition is approached.

A set of 480 samarium cobalt permanent magnets produces a linearly polarized wiggler magnetic field. The wiggler is 60 periods long, with periodicity $\ell = 2.0$ cm. The wiggler amplitude is variable from 0.1 to 1.0 kG.

The beam drift tube is a length of WR-137 band rectangular waveguide. The 6 GHz FEL output frequency lies in the lowest (TE_{10}) mode of the waveguide. A calibrated crystal detector and a conventional spectrum analyzer are used to make microwave power and frequency measurements. Determination of the electron beam axial velocity distribution is made using a gridded Faraday cup. At these low beam voltages, it is possible to use a repelling grid in the cup. Measurement of the beam properties and the microwaves can be made simultaneously.

d. An Intermediate Energy, Long Pulse Free Electron Laser

An intermediate energy free electron laser experiment designed to investigate cyclotron resonance effects is being carried out on the Pulserad 615 MR electron beam facility. The experimental parameters are given in the table below:

Beam Energy (keV)	150–200
Beam Current Density (A–cm^{-2})	70
Pulse Length (μs)	2
Axial Magnetic Field (kG)	0.7–7.0
Wiggler Field Amplitude (kG)	0–1.5
Wiggler Period (cm)	3.3
Number of Periods	50

The Pulserad 615 MR power source is a Marx generator which produces a repeatable, flat accelerating voltage pulse. It has the capability of operating with a thermionic (hot cathode) electron gun. In this experiment the thermionic cathode is immersed in a shaped focusing magnetic field. The perpendicular energy of the emitted electrons is estimated to be less than one percent of their total energy. This characteristic of the electron beam is important in free electron devices from the standpoint of producing coherent radiation with high efficiency.

The beam propagates in a two meter long drift tube, guided by a uniform axial magnetic field that can be varied between 0.7 and 7.0 kG. The wiggler fields are generated by a bifilar helical winding. An adjustable, adiabatic entrance profile is produced by staggering the wiggler termination windings.[3] This termination scheme allows us to increase the wiggler field amplitude to its full value slowly and with any amplitude profile desired at the upstream end of the wiggler. Computer simulations have shown that the entrance profile is very important in preserving low beam energy spread in both the transverse and axial directions as the beam enters the wiggler field. The system has been designed so that under normal operating conditions, the emitted radiation propagates in the lowest mode of the cylindrical drift tube.

We have observed microwave power levels of over 10 kW at approximately 10 GHz. Spectra observed with an X-band waveguide dispersive line show that most of the power is concentrated in a narrow peak ($\Delta f/f < .01$). Preliminary results indicate that the output frequency increases with beam energy with the functional form predicted by theory.

Measurements of the beam current have been made in the vicinity of the resonance $k_w v_o = \Omega_o$ that occurs when the cyclotron frequency of the guide magnetic field equals the frequency $k_w v_o$ associated with the wiggler (k_w = wiggler wave number). As the axial magnetic field is increased and passes through the resonance, the beam current transmitted through the wiggler drops sharply. Beyond this point, the current increases slowly to its original value. Measurements of microwave power levels and spectra near resonance are underway.

e. A Submillimeter Free Electron Laser using a High Quality Electron Beam

In this experiment, a high current density, high energy electron beam is used to produce submillimeter wavelength radiation. The measured parameters of the electron beam are:

Beam Voltage	1.6 MV
Beam Current Density	200 A–cm^{-2}
Axial Momentum Spread	$\leq$ 1%

Other experimental parameters are as follows:

Wiggler Period	2.0 cm
Number of Periods	50
Wiggler Field Amplitude	1200 Gauss
Output Frequency	456 GHz
Theoretical Single Pass Gain	23 dB
Saturated Efficiency	0.75%

The M.I.T. Pulserad 110A accelerator facility is used in conjunction with a five stage electrostatically focused field emission electron gun to produce a high quality intense relativistic electron beam. The beam is then guided into a bifilar helical wiggler field by means of a short solenoidal coil which acts as a focusing lens. The coil is positioned upstream of the wiggler and obviates the necessity of having a guiding magnetic field in the wiggler region. The lack of a guide field in the wiggler region eliminates the possibility of exciting the cyclotron maser instability.

The beam quality has been determined by measurements of beam emittance and beam momentum spread.[4] Emittance measurements were carried out by allowing the beam to impinge on an array of pinholes in a brass disk, and then observing the transmitted beamlets on a fluorescent screen at a known distance downstream. We find that the normalized emittance is $\leq$ 50 mr–cm. Beam momentum spread measurements were carried out using a magnetic spectrometer. The spectrometer is of the Browne–Buechner type and is capable of a resolution in $\gamma v_{\parallel}$ of less than 0.1%. Both time integrated and time resolved measurements carried out on this electron beam show an axial momentum spread of less than one percent.

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18.2 Tokamak Research: RF Heating and Current Drive

U.S. Department of Energy (Contract DE-AC02-78ET-51013)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

The main theme of the Versator II program is to understand interactions between externally excited lower-hybrid waves and tokamak plasmas. For typical tokamak plasmas, the lower-hybrid wave has a frequency in the range of a few hundred MHz to a few GHz. In current experiments, the lower-hybrid wave is generated by a RF system which consists of a 150 kW, 800 MHz klystron, and a waveguide power splitter with four output channels. The phase of each output can be continuously adjusted ($0° \sim 360°$) with mechanical phase shifters. Such phase control allows traveling wave spectra to be launched either parallel or antiparallel to the direction of the electron ohmic drift, $\Delta\Phi = \pm 90°$, or a standing wave spectrum can be excited with $\Delta\Phi = 180°$.

Versator II is a medium-size tokamak with the following important physical and plasma parameters: major radius $R = 40.5$ cm, limiter radius $a = 13$ cm, toroidal field $B_T \sim (8\text{–}15)$ kG, plasma current $I_p \sim (30\text{–}60)$ kA, discharge length $\tau_{pulse} \sim (30\text{–}40)$ ms, central electron temperature $T_{eo} \sim (250\text{–}450)$ eV, central ion temperature $T_{io} \sim (120\text{–}180)$ eV, line average density $\bar{n}_e \sim (0.1\text{–}3) \times 10^{13} \text{cm}^{-3}$ and $Z_{eff} \sim 2$.

The phase velocity of the lower-hybrid wave can be controlled by adjusting phases between launching waveguides. With proper phase velocity and plasma parameters (e.g., density, toroidal magnetic field, etc.), the lower-hybrid wave will interact with either plasma electrons or ions. Consequently, the physics problems of heating (electron or ion) and current generation by lower-hybrid waves can be studied.

The emphases of these experiments in 1983 are on the toroidal effects of wave penetration; by making a comparison of launching waves through a top port and a side port at the same toroidal position. Important experimental results and detailed diagnostic measurements are summarized below.

Present Statu

18.3 I. Lower-Hybrid Current Drive (LHCD) Experiment

18.3.1 Top Launching vs. Side Launching

Ray tracing theory[1] has shown that traveling waves launched from the top of the torus in the direction $\hat{S} = \vec{B}_T \cdot \vec{I}_p \hat{\Phi}/|B_T||I_p|$ (where $\hat{\Phi}$ is the toroidal unit vector) experience an upshift in their $n_{\parallel}(= ck_{\parallel}/\omega)$ due to toroidal effects. Generally, for top launching in the $+\hat{S}$ direction, the wave slows down along field lines and is often absorbed in the first poioidal transit through the center of the plasma. However, when waves are launched from the midplane on the outside, $n_{\parallel}$ downshifted initially, making first pass absorption less likely due to the difficulty in satisfying the Landau resonance condition. In general, top launching is expected to give improved power absorption efficiency and an interaction with lower energy electron when compared with side launching. Measurement of comparative current drive efficiency with couplers mounted on the top and side of the torus therefore appears to be a test of the ray tracing prediction of toroidal shifts in $n_{\parallel}$. Nevertheless, it should be noted that according to a very simple picture of Fisch current drive theory,[2] the merit factor of current drive $I_{RF}/P_{RF} \propto 1/n_{\parallel}^2$, so the $n_{\parallel}$ upshift is expected to result in reduced current drive efficiency.

Table 1

	4-Guide Top	4-Guide Side	6-Guide Side
$\Delta\Phi$	+90°	+90°	+90°
$N_{\parallel o}^{PEAK}$	8	8	8
$\bar{n}_e$	$4\times10^{12}cm^{-3}$	$4\times10^{12}cm^{-3}$	$4\times10^{12}cm^{-3}$
I_p	36 kA	36 kA	32 kA
P_{NET}	13 kW	11 kW	8 kW
ΔI	3.0 kA	5.3 kA	3.5 kA
Δt	5 msec	5 msec	5 msec
$\tau_{L/R} \simeq$	15 msec	15 msec	15 msec
$I_{RF} \simeq \frac{\Delta I}{\Delta t} \tau_{L/R}$	9.0 kA	16 kA	13 kA
$S = \bar{n}_{15} \frac{R_o I_{RF}}{P_{NET}}$	0.11	0.23	0.26

A comparison of current drive efficiencies between side and top launching experiments